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Surface Mooring Survivability In the Littoral Regime

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INTRODUCTION

Research on cyclic fatigue of mooring components has shown that it is possible to quantify fatigue failure of mooring components. However, there does not exist at this time a specific design procedure or manual that can be passed on to oceanographic engineers for designing future moorings, especially those having hardware that has not been previously tested in the laboratory. The objective of this project was to develop and document a set of design procedures for shallow-water moorings that can easily be applied by oceanographic engineers to quantify fatigue damage in any type of mooring component.

METHODS AND MATERIALS

Our approach combined full-scale experiments at the Woods Hole Oceanographic Institution (WHOI) Buoy Farm and laboratory cyclic testing of mooring components. A full-scale test mooring was designed with an in-line string of ½-inch chain shackles that were predicted to experience very high cyclic loading. The mooring was deployed at the WHOI Buoy Farm during the winter storm season, until one of the shackles failed. Mooring line tension was measured throughout the deployment to document the loading history. Laboratory testing of the similar number of new ½-inch chain shackles was used to develop probability distributions for fatigue strength. The probability distributions will be used with the measured loading history and the Palmgren-Miner damage rule to predict when a failure of the Buoy Farm mooring should have occurred. Comparison with the actual time of failure will help us develop safety factors to account for random loading and corrosion.

RESULTS

A surface mooring (Figure 1) with a three-meter discus buoy was deployed on October 8, 1999. The surface buoy was instrumented with a motion package and load cell. The mooring contained a string of 20 ½-inch shackles approximately three meters below the buoy bridle. To

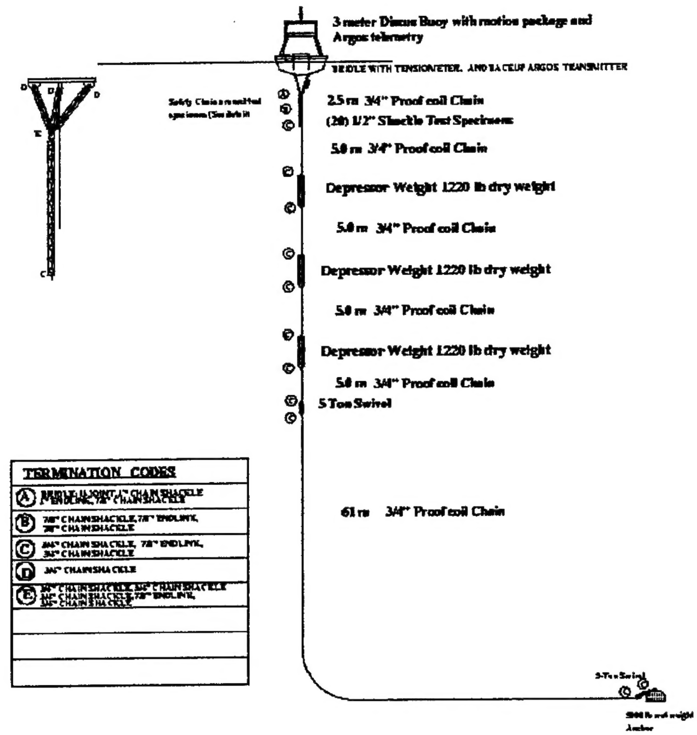

Figure 1. Surface mooring deployed at WHOI Buoy Farm

simulate a typical subsurface instrument load, three 1200-pound depressor weights were placed in line on the mooring below the test shackles. The test shackles were intentionally smaller than the conventional ¾-inch shackles normally used on such a mooring so that they would lose a significant percentage of their fatigue life over the course of the winter deployment. A safety chain paralleled the test specimens. As planned, one of the ½-inch shackles failed after 125 days. Though this is a single data point, it provides an actual mooring component failure along with the complete load history.

Laboratory hardware testing of new and used ½-inch shackles was performed. The tests involved low stress and a number high cycles leading up to failure. The used shackles were the unbroken samples from the Buoy Farm mooring. Figure 2 shows the results for the tests on new and used ½-inch shackles. Each series of tests involved n=18 components. The load range for these tests was 3,000-5,000 lbs, which was a typical load range seen by the full-scale mooring during rough weather. As reference, the mean ultimate strength of 11 new ½-inch shackles was measured to be 41,200 lbs with a standard deviation of 1,900 lbs. Tests on each part were suspended after 5×10^6 cycles if no failure had occurred. In both cases (new and used tests), there was a group of parts that failed in less than 5×10^6 cycles and a second group (containing an equal number of parts) that never failed.

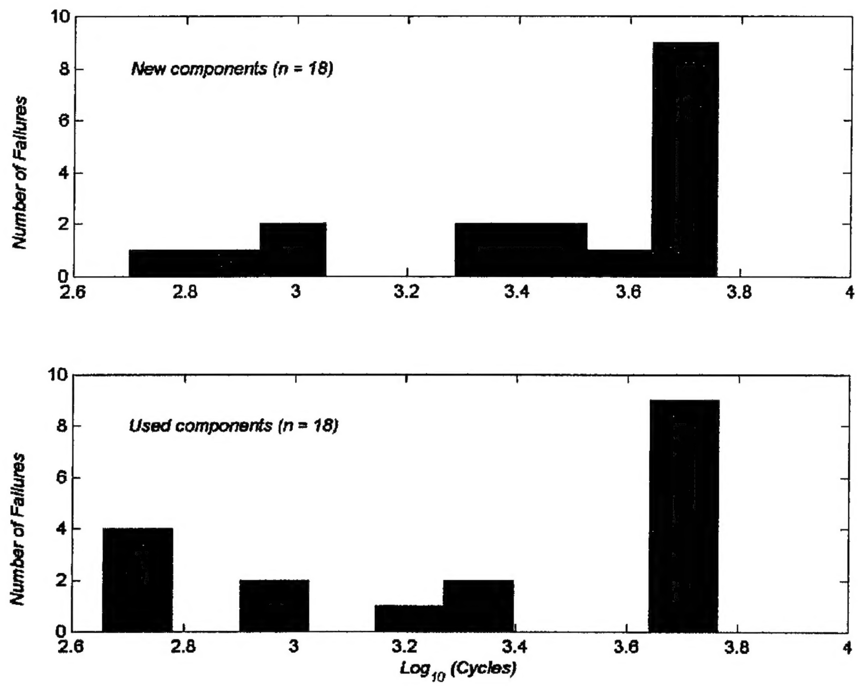

Figure 2. Histograms showing number of failures that occurred during laboratory fatigue tests involving new and used ½-inch shackles. The used shackles had been deployed for 125 days on an engineering test mooring at the WHOI Buoy Farm.

DISCUSSION

Our hypothesis is that the group of parts that failed during the laboratory tests and during the full-scale deployment contained initial flaws larger than a critical value (perhaps associated with the galvanizing process). In the case of the used parts, the flaws grew in response to the loading experience during the full-scale deployment. For one part (i.e. the part that broke) on the Buoy Farm mooring, the flaw reached a length that caused failure. For the other used parts that were recovered, crack growth resulted in components with less fatigue resistance then new parts. The key is that we can quantify this difference through the following statistical analysis.

Let Y be the lifetime of a part. A flexible model for lifetime is the Weibull model with survivor function:

$$S(y) = prob(Y \geq y) = \exp(-(y/\alpha)^{\eta})$$

Under the Weibull model, the mean of Y is:

$$\alpha \Gamma(1 + \frac{1}{\eta})$$

and variance:

$$\alpha^2(\Gamma(1+\frac{2}{\eta})-(\Gamma(1+\frac{1}{\eta}))^2)$$

where Γ is the gamma function.

Under the simplest model, the lifetime of a new part is assumed to follow a Weibull distribution with parameters α_{new}, η while the lifetime of a used part is assumed to follow a Weibull distribution with parameters α_{used}, η. Note that the shape parameter η is assumed to be the same for new and used parts. This assumption can be checked and, if necessary, relaxed. Interest centers on testing the null hypothesis $H_o : \alpha_{new} = \alpha_{used}$ against the one-sided alternative hypothesis $H_1 : \alpha_{new} > \alpha_{used}$. It is natural to base the test on the likelihood ratio statistic:

$$\Lambda = -2(\log L_o - \log L_1)$$

where L_o and L_1 are the values of the likelihood maximized under H_o and H_1, respectively. The log likelihood function is given by:

$$\log L = \sum_{uncensored} \log f(y_i) + \sum_{censored} \log S(c_i)$$

where f is the Weibull density (i.e., $f = -S'$) and c_i is the censoring point for censored observation i. The null hypothesis is rejected in favor of the one-sided alternative at significance level α if the observed value λ of Λ exceeds the upper 2α-quantile of the chi-squared distribution with 1 degree of freedom. **Analysis under this simple model revealed no significant difference between new and used parts.**

Under a slightly more complicated model, each part, whether new or used, has a common probability p of effectively infinite lifetime but, conditional on lifetime being finite, the previous model holds. For this model, the log likelihood function is:

$$\log L = \sum_{uncensored} \log((1-p)f(y_i)) + \sum_{censored} \log(p + (1-p)S(c_i))$$

and the analysis proceeds as before. In this case, H_o is decisively rejected (significance level = 0.007). With lifetime measured in 10^6 cycles, the maximum likelihood estimates for this model are:

$$\hat{p} = 0.45 \quad \hat{\alpha}_{new} = 3.1 \quad \hat{\alpha}_{used} = 1.2 \quad \hat{\eta} = 1.5$$

Conditional on finite lifetime, the estimated mean and standard deviation of lifetime are 2.80 and 1.90 for new parts and 1.08 and 0.74 for used parts. Next, let *Y(x)* be the lifetime of a part subject to a load *x*. The basic model is that *Y(x)* has a Weibull distribution with parameters:

$$\alpha(x) = \alpha_o x^{-\alpha_1} \qquad \alpha_o, \alpha_1 > 0$$